Failure analysis of dissimilar single-lap joints

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ABSTRACT. Single-lap joints made of aluminium and carbon fibre adherends of different thickness are tested to understand better the behaviour of such dissimilar joints. The overlap length and the thickness of the adhesive are kept constant. Local deformation fields are monitored by using the digital image correlation method. Peeling and shearing strains are investigated, emphasizing that peeling is important in the region where failure is initiated, towards an extremity of the overlap region. The use of only carbon fibre adherends is not recommended for a smaller thickness as an additional interface failure is produced and compromises the integrity of the lap joint. However, a dissimilar joint (aluminium-carbon) with smaller thickness adherends succeeds to maintain the stiffness of the assembly, but its strength is diminished. The obtained results are suggesting that a complete monitoring of the failure processes in the overlap region can be fully understood only if local deformation measurements are possible.

KEYWORDS. Sigle-lap joints; Dissimilar adherends; Digital image correlation; Peeling and shearing.

INTRODUCTION

A eronautical, automotive or naval structural integrity is of great importance and any presence of imperfections can reduce significantly the load bearing capacity. Without a better understanding of progressive failure, the fracture criteria and predictive capabilities will be limited. In many cases adhesive joints have to be used and single-lap joints are of particular interest. Several parameters have a significant influence as: the thickness of the adherends, the overlap length, and the adhesive thickness. On the other hand, the use of dissimilar materials in such joints represent new challenges and the complete understanding of the local phenomena deserve further investigations. In many engineering applications the gluing of metallic and composite materials starts to be a necessity.

It is known that the thickness of the adhesive influences the strength of the assembly but its effect is not completely understood. Experimental results have shown that the strength of the joint decreases with the increase of the adhesive thickness. Gleich et al. [1] showed that the interface stresses grow proportionally with the thickness, and Grant et al. [2] pointed out through experimental testing that the strength decreases due to the increase of the bending moment. The increase of the thickness leads to the increase of the arm of the force and therefore of the bending moment. It looks like the optimum strength of an epoxy adhesive is to be obtained when its thickness is between 0.1 and 0.5 mm. However, as pointed by Banea and da Silva [3], the results may vary due to the type of loading, the ductile or fragile behaviour of the adhesive and the rigidity of the adherends. Opposite to what was expected, they showed that for a fragile adhesive a better performance of the lap-joint was obtained for the thicker adhesive. An explanation of the peculiar behaviour relied on the different thermal inertia of the thicknesses which resulted after the thermal cycle. The contradiction between the classical

elastic analysis and the experimental results generated further studies of da Silva et al. [4]. The adherends were made from steel as to diminish the level of deformations. Their conclusion suggests that the stresses at the interface adherend-adhesive are responsible for the strength decrease when the thickness of the adhesive increases. A different approach is proposed by Matihas and Lemaire [5] which emphasize that in engineering applications the thickness of the adhesive is seldom constant and a probabilistic analysis is needed to study the reliability of such adhesive joints. They used aluminium and carbon fibre adherends of constant thickness and using Volkensen's model calculated a coefficient of safety for which the probability of failure should be below 0.01%. Their results pointed out that a thicker adhesive will help in reaching the reliability goal, that is contrary to the experimental findings obtained in [1, 2, 4].

The increase of the adherend thickness diminished the peeling effect at the extremities of the adhesive length and led to the increase of the shearing strength of an epoxy adhesive [6], and the increase of the adhesive overlap length increased the failure force of the assembly [7], but in fact the strength of the adhesive layer diminishes. In [8] different adhesives were used for single-lap joints of carbon fibre adherends with an overlap between 10 and 80 mm. For a ductile adhesive the failure force increases with the increase of the overlap, but for a fragile adhesive the force increases only up to 30 mm overlap and afterwards decreases due to the interlaminar failure of the adherends. In [9], when increasing the thickness of the steel adherends from 1 to 5 mm the maximum force and failure strength increases as already established in other studies.

A complex analysis was performed by da Silva et. al [10] which analysis the influence of several parameters (stiffness of adherend, thickness of adherend, thickness of adhesive, overlap length) on the strength of the single-lap joint by using the Taguchi method. Starting from an initial configuration the influence of each parameter is quantified as giving a maximum percentage increase of the strength of the assembly. The increase of the values of the analyzed parameters is beneficial to obtain strength increase with specified values, with one exception, the thickness of the adhesive, by which increase the strength of the single-lap is diminished. It was also noticed that the different procedures used to prepare the surfaces to be glued haven't influenced the obtained results.

The digital image correlation (DIC) method has inspired several researchers to analyze the strength of lap-joints. Moreira and Nunes [11] investigated the behaviour of a flexible adhesive and the critical shearing deformations which decrease towards the ends of the overlap, suggesting that the peeling strains are responsible for the initiation of the failure. They pointed out that it is essential to consider the peeling effects for the correct interpretation of the strength of the joint. Moutrille et al. [12], Nunes and Moreira [13], and Silva and Nunes [14] used also DIC for studying several geometrical configurations and successfully analyzed the influence of the aforementioned different parameters on the shearing strength of the joints.

In this article the type and the thickness of the adhesive as well as the overlap length are kept constant. The single-lap joints are configured by using aluminium and carbon fibre adherends of 3 mm and 5 mm thickness combined differently. DIC is used to monitor the local failure in the adhesive and give insides on the particular phenomena. Peeling (opening or mode I) and shearing (mode II) deformations are analyzed in detail and some conclusions concerning the particularities of using dissimilar adherends are drawn. It is emphasized that only local measurements, in the overlap region, can provide correct information about the deformation and failure of the adhesive.

TESTED CONFIGURATIONS AND MATERIALS

The single-lap joints used in the investigations have the dimensions presented in Fig. 1. The thickness of the adhesive is kept constant to 0.5 mm and the overlap length is 20 mm. The thickness *t* of the adherends was changed from one configuration to another. The adherends were made from aluminium or carbon fibre. At the ends of the overlap a 5 mm gap is kept on each side of the overlap as used to control the thickness of the adhesive layer with a wax layer of 0.5 mm.

The adhesive used in the experiments is Araldite 2015 with the elastic constants established with DIC on bulk specimens as: longitudinal modulus of elasticity $E = 1790$ MPa and Poisson's ratio $\nu = 0.32$. This adhesive has a ductile behaviour.

The adherends were made from aluminium 6060 T6 and unidirectional carbon fibre of 250 g/m² with epoxy resin matrix. The considered thicknesses of the adherends for both materials were either 3 mm or 5 mm, having all of them a width of 30 mm. The adherends were further denoted as *aluminium* and *carbon* having the thickness indicated afterwards. The elastic constants of these adherends were established through traction tests on bulk ISO standardized specimens, as indicated in Tab.1. Tests were done on a Zwick Z010 (10 kN) machine. Speed of testing was of 1 mm/min.

The increase of stiffness of the 3 mm carbon adherend can be explained due to the higher volume fraction of carbon fibres which resulted for this thickness.

The single-lap joint prepared for DIC measurements is shown in Fig. 2. On the left side it is better noticed the uneven surface due to the wax of constant 0.5 mm thickness which filled the overlap for 5 mm on each side as to control the adhesive thickness.
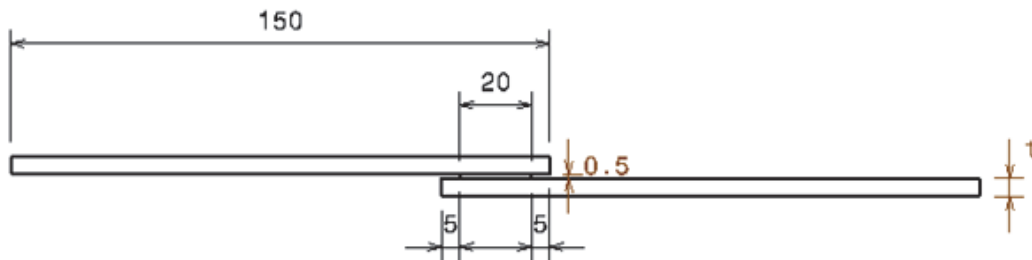

Figure 1: Dimensions of the single-lap joints.

	Aluminium	Carbon 3 mm	Carbon 5 mm
Modulus of elasticity [MPa]	70000	76000	64000
Poisson's ratio	0.33	0.35	0.37

Table 1: Elastic constants of adherends.
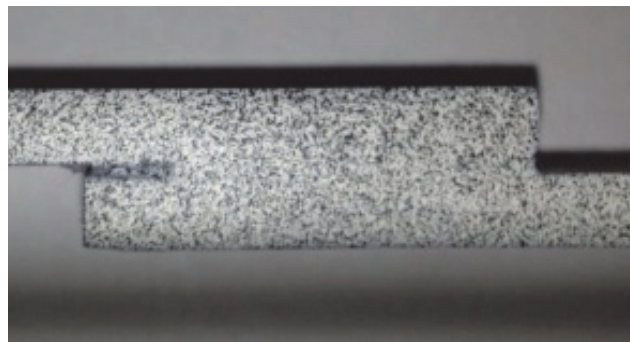
Figure 2: Surface of a single-lap joint prepared for DIC measurements.

Overall, six different geometrical configurations were used for testing, as mentioned in Tab.2. For each configuration five lap joints were tested. If the failure was not cohesive the test was disregarded.

	Adherend 1		Adherend 2	
	Material	Thickness	Material	Thickness
Configuration 1	aluminium	3 mm	aluminium	3 mm
Configuration 2	carbon	3 mm	carbon	3 mm
Configuration 3	aluminium	3 mm	carbon	3 mm
Configuration 4	aluminium	5 mm	aluminium	5 mm
Configuration 5	carbon	5 mm	carbon	5 mm
Configuration 6	aluminium	5 mm	carbon	5 mm

Table 2: Configurations used for testing with aluminium and carbon adherends of different thickness.

The relative displacements between the adherends were monitored in the overlap region and both peeling and shearing deformations were measured by using DIC.
For each configuration out of the five performed tests only the representative one was chosen for further comparisons. Plots of the shearing stress as a function of the displacement between the grips as indicated by the testing machine were also represented.

EXPERIMENTAL EVALUATION OF LOCAL DEFORMATIONS

The lateral surface of the single-lap joint was analyzed by using DIC. The ARAMIS 2M system was used to measure the deformations of the adhesive. For all tests a calibre of 35 x 28 mm was considered. One frame per second was acquired. In order to obtain a map of the deformations along the overlap length three virtual gauges were chosen on each side of the overlap as seen in Fig. 3. Configuration 4 is presented in the figure, both adherends being aluminium of 5 mm thickness. Top and bottom gauges are positioned on the edges of the adhesive layer. The relative displacements of the adherends are measured along the x axis as to investigate the peeling deformation and the corresponding strain, and along the y axis to monitor the shearing displacement of the adherends and the shearing strain.

Local peeling strains are shown with their values in Fig. 3. A maximum strain of about 9 % was obtained at the lower extremity of the adhesive shortly before the failure of the joint. As getting towards the middle region of the overlap compression is produced in the adhesive, thus indicating the bending of the adherends.
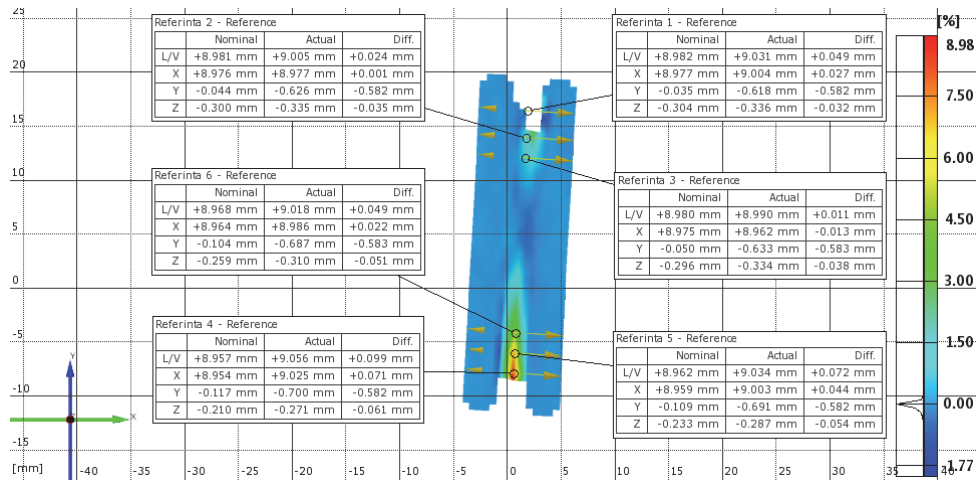

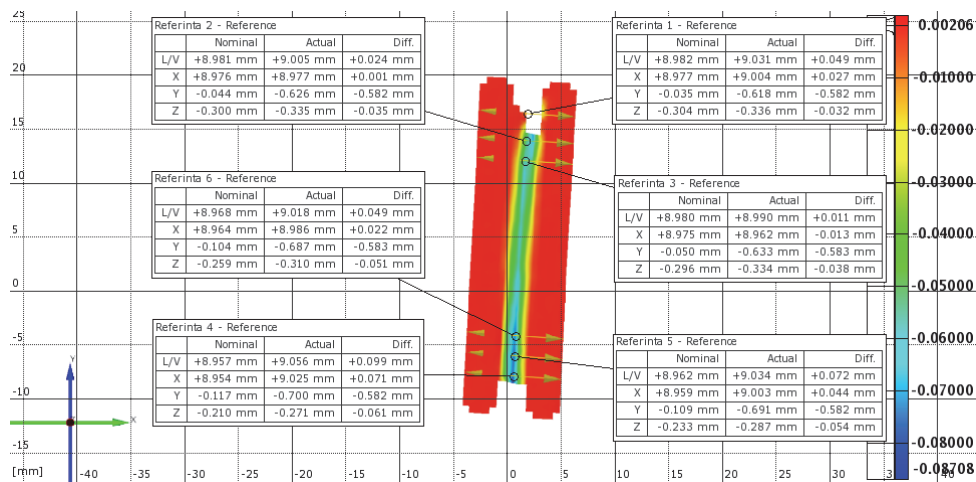Figure 3: Peeling relative strains in the adhesive.

Figure 4: Shearing strain in the adhesive along the overlap.

Shearing is produced along the whole overlap length and values of the shearing strain can be depicted in Fig. 4. The same frame as in Fig. 3 is presented. Shearing is mainly constant in the adhesive with a maximum value, again, towards the lower extremity of the overlap. An initial crack started from there and propagated. This is due to the possible slightly unsymmetrical geometric arrangement of the single-lap joint.

BEHAVIOUR OF LAP JOINTS MADE OF DISSIMILAR ADHERENDS

As different adherends were used for understanding the behaviour of similar and dissimilar single-lap joints, we initially tested aluminium adherends of 3 mm, respectively 5 mm thickness (configurations 1 and 4). Shearing stress is represented as a function of the displacement of the grips measured by the testing machine. The shearing stress is an average value and is calculated as the ration between the force and the surface of the adhesive overlap. The measured displacement includes the deformations of the adhesive, of the adherends, and a possible slippage of the adherend in the mechanical grips, although this was not evident by analyzing the specimen after failure. This is why this value is greater than the one measured by using DIC.

From Fig. 5 it is to be noticed that the stiffness of the joint is increased for the thicker aluminium adherend. As stiffness decreases (3 mm) the peeling effect is greater and the joint fails at a smaller force.
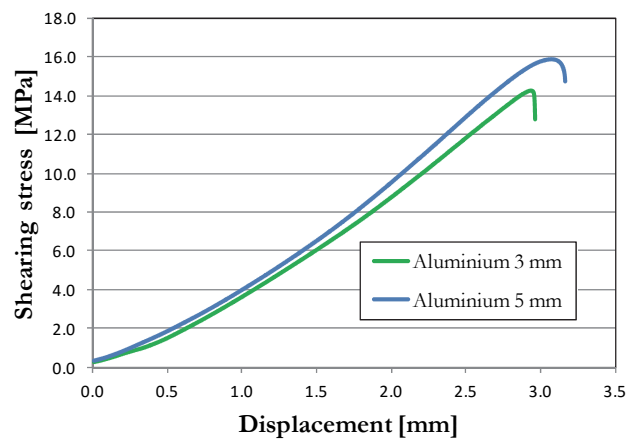

Figure 5: Influence of the aluminium adherend thickness.

In Fig. 6, for carbon adherends, it is to be noticed that for a thickness of 3 mm the stiffness is lower than for a thickness of 5 mm (which is not surprising). However, the failure force is much smaller and the shearing stress decrease to about 11 MPa. Failure is produced suddenly, without a decrease of the maximum force as happens for the 5 mm thickness.
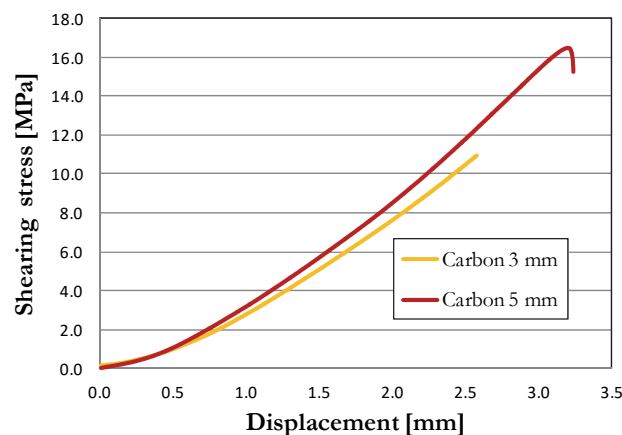

Figure 6: Influence of the carbon adherend thickness.

For carbon adherends a delamination between the layers of the adherend appears especially for the 3 mm thickness adherends (configuration 2). The strength of the joint is in fact dictated by the interface strength of the carbon laminas and not given by the cohesive strength of the adhesive. If the interface strength is assumed to be constant regardless the thickness of the carbon adherends it results that a lower stiffness will lead to a higher peeling force as the thickness of the adherend is decreased. One can notice in Fig. 7 the pull-out of the carbon fibres due to the interlaminar failure of the adherend.
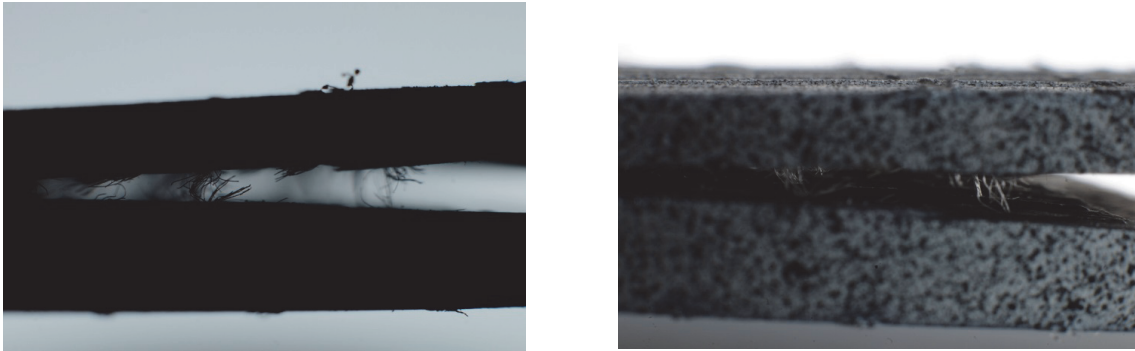

Figure 7: Interlaminar failure of the 3 mm carbon adherend.

It is also recommended to avoid any mechanical machining or scratching on the surface of the carbon adherend as to increase its roughness prior to the application of the adhesive. This may also contribute to the unexpected interlaminar failure.

For adherends of 5 mm thickness the shearing failure stress is about 16 MPa regardless the joint configuration (Fig. 8). A slightly larger displacement until failure is obtained for the aluminium-aluminium lap joint (configuration 4). However, the aluminium-carbon lap joint is stiffer but fails sooner.
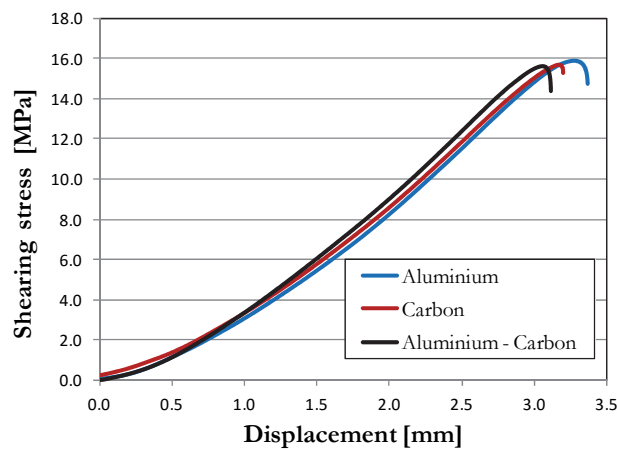

Figure 8: Influence of material combinations for 5 mm adherend thickness.

For 3 mm adherends, as to be seen in Fig. 9, the best results were clearly obtained for aluminium adherends, that is maximum shearing stress and maximum displacement at failure. If one of the adherends was carbon, interlaminar failure resulted eventually. Lower stiffness is undesirable as it increases the bending of the adherend and the peeling stresses in the adhesive.

The global values of the displacements of the single-lap joint measured through the displacement of the grips of the testing machine is at failure about 3 mm for the 5 mm adherends, and about the same value or less for the 3 mm adherends (not less than 2.5 mm). This globally measured displacement is significantly larger than the local relative displacements of the adherends measured on x and y directions (Figs. 3 and 4 for aluminium adherends) with DIC. Only the local relative displacements are reflecting the correct behaviour of the adhesive.
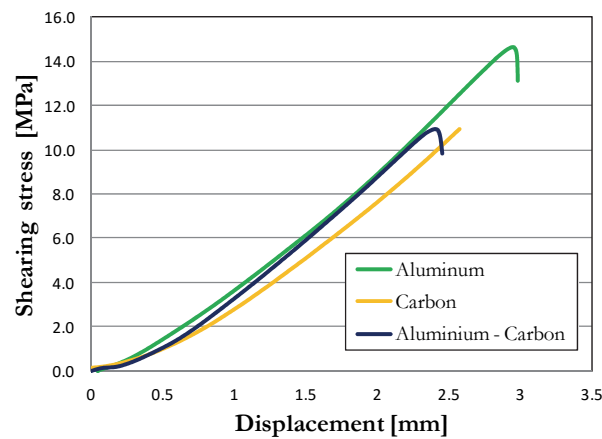
Figure 9: Influence of material combinations for 5 mm adherend thickness.

LOCAL DEFORMATIONS OF SINGLE-LAP JOINTS

Shortly before the failure of the single-lap with 5 mm aluminium adherends the relative peeling displacement between the adherends is about 0.07 mm (Fig. 3 or Fig. 4) along the x axis at the lower extremity of the overlap as measured by the first virtual gauge, then becomes 0.04 mm in the next virtual gauge, and 0.02 mm in the third virtual gauge; so the peeling displacement decreases rapidly. Failure initiated from this region. In the other side of the overlap the relative displacements are smaller. The shearing displacement along the y axis is 0.58 mm; this value remains mainly constant along the overlap length at this stage of loading.

A comparison of the results obtained for relative shearing displacements is given in Fig. 10 for 5 mm adherends (configurations 4, 5, and 6). The three adherends combinations behave quite similarly (see also Fig. 8) but the local relative displacements are much smaller. The carbon-carbon joint behaves very well for this thickness; on the contrary the aluminium-carbon joint fails sooner, although it is stiffer. Probably some delaminations in the carbon adherend were produced for this particular test. Maximum relative shearing displacements are about 0.5-0.7 mm, much smaller than the ones obtained in following the indications of the testing machine.
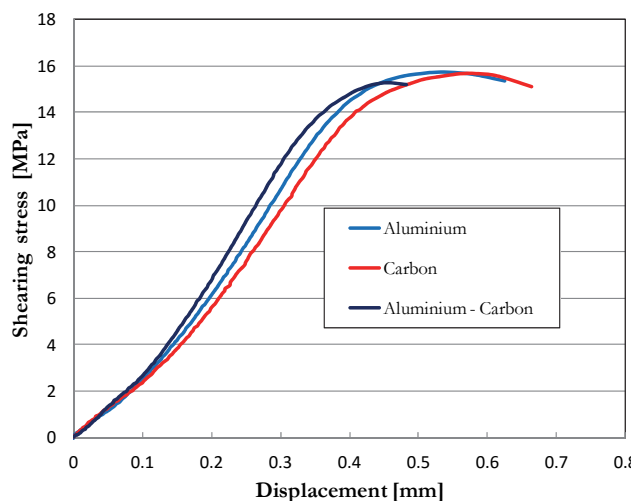

Figure 10: Relative shearing displacements for adherends of 5 mm.

The 3 mm adherends give a satisfactory behaviour, as before, only for the aluminium adherends (configuration 1). Smaller thickness and stiffness carbon adherends imply higher bending moments and delamination of the carbon layers. Failure is produced sooner for configurations 2 and 3, at less than 0.2 mm relative shearing displacement (Fig. 11).

As commented before, local relative displacements are much smaller - less than 0.3 mm, that is 10 times smaller than the global displacements (see Fig. 9).

If we analyze the peeling and shearing displacements for the aluminium and carbon adherends of 3 mm (Fig. 12) where failure will initiate it is evident that the peeling deformations are much smaller. For the carbon adherends these deformations indicate an initial negative displacement, which has the significance of the reduction of the initial gauge length due to the local bending effects which are more pronounced for this thickness. At higher forces the peeling is evident (at about 10 MPa shearing stress) and the lap joint fails soon afterwards. As mentioned before, additional delaminations between the carbon fibre laminas are accelerating the failure event.

For both adherends the peeling deformations cannot be neglected and influence the moment of failure although they are of small values.
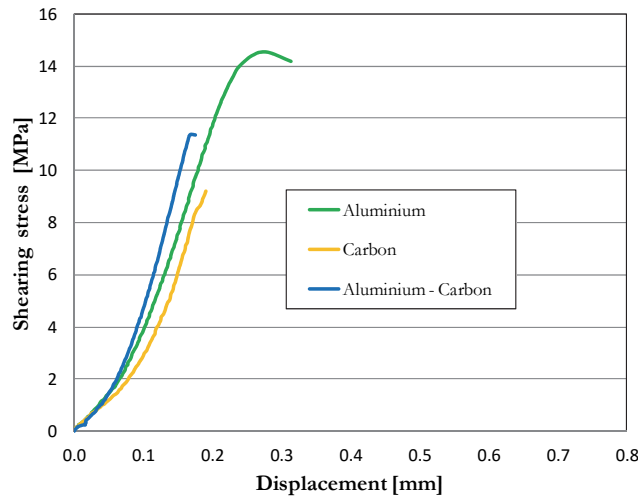

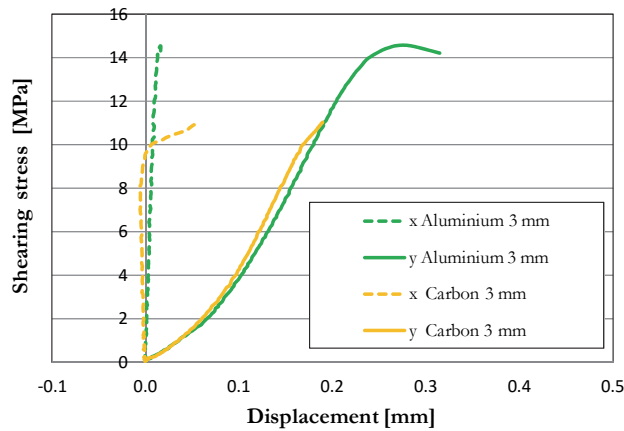Figure 11: Relative shearing displacements for adherends of 3 mm.

Figure 12: Variation of local relative displacements for aluminium and carbon 3 mm adherends.

CONCLUSIONS

The use of dissimilar single-lap joints is of great importance and this is why it is investigated in this article. By keeping constant the overlap length and the thickness of the adhesive we analyze the influence of the thickness and material (aluminium or carbon fibre) of the adherends.

Digital image correlation measurements done in the immediate vicinity of the adhesive layer can provide correct information about the shearing and peeling deformations. It was shown that failure initiates where peeling is significant. For carbon fibre adherents, especially for the lower thickness of 3 mm, additional interlaminar damage compromises the integrity of the joint and leads to premature failure of the assembly. Dissimilar joints (aluminium-carbon) with smaller

thickness adherends succeed to maintain the stiffness of the assembly as compared to the aluminium joints, but their strength is diminished by the pull-out and delamination of carbon fibres.

It is of great importance to rely on local deformation measurements and not on the global ones as indicated by the testing machine, which include also the deformation of the adherends. Only by using such an approach a proper understanding of adhesive failure is possible.

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